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14.ABSTRACT

A program has been initiated to develop and demonstrate the applicability of time-of-flight and Doppler-based optical velocimetry techniques to supersonic micro scale flow fields. In particular, Molecular Tagging Velocimetry (MTV) measurements have been performed, using acetone vapor as a molecular tracer, in the flow produced by a 1 mm diameter, pressure matched, sonic nozzle. Measurements were performed over a static pressure range from ~ 1 torr to ~ 20 torr. Measurement accuracy is found to be on the order of 5 m/sec at a spatial resolution of order 10 microns. As a compliment to the experimental measurements, a computational program was also initiated which focused on the development of in house Navier - Stokes and Direct Simulation Monte Carlo (DSMC) codes.

15.SUBJECT TERMS

Micro Nozzle, Optical Velocimetry, Molecular Tagging

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DEVELOPMENT AND APPLICATION OF ADVANCED OPTICAL DIAGNOSTICS FOR THE STUDY OF HIGH SPEED FLOWS IN MICRO SYSTEMS

AFOSR GRANT - F49620-00-1-0169
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Final Report - December 21, 2000

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Introduction

The development and application of micro devices and systems has experienced much recent growth and this trend is expected to continue for years to come. Gaseous flow through and within such devices is a principal consideration in many applications and its understanding can be crucial for optimization of performance. While the last 10 years has seen enormous progress in the general areas of Micro Electro Mechanical Systems (MEMS) design and fabrication, detailed understanding of fundamental physical flow processes on these small scales has lagged due to a lack of suitable measurement and computation tools. **This 9 month program, focused on demonstrating the potential utility of quantitative velocimetry techniques for application to supersonic micro-nozzles, such as those, which might be employed for flow control and/or small satellite orbit maintenance.** In parallel, the development of in-house computational codes, based on incorporation of slip boundary conditions into the two-dimensional Navier Stokes equations and, at lower densities, Direct Simulation Monte Carlo (DSMC) was also initiated.

Objectives

This 9 month program represents the first phase of a requested three year program in compressible, microfluid flow. The overall goal of the entire program is to develop and demonstrate predictive capability in two-dimensional, compressible free jet and wall bounded micro scale flows over a range of conditions and Mach numbers. The stated objectives of the full program focus on addressing the following specific questions:

1. How do viscous effects quantitatively influence boundary layer growth in micro scale converging - diverging nozzles and can micro nozzles be designed to deliver supersonic flow over a wide range of stagnation conditions and Mach numbers?

2. Over what range of conditions can quantitative velocity data be obtained, and what is the practical limit of spatial resolution?

3. How is the velocity profile in the boundary layer developed over a flat plat affected as the flow evolves from the continuum to slip to transition regimes and can experimental measurements be used to improve computational predictions?

Due to time and funding constraints, the first phase 9 month program focused on objective two. Work was also initiated on objective 1.

Approach

Microflows are parameterized by the Knudsen number, $Kn = \lambda/\delta$, where λ is the molecular mean free path and δ is a characteristic flow length scale, which is typically a dimension of the device or system. While there are some differences in the literature, the following is a typical breakdown of how the Knudsen number delineates the possible flow regimes (Piekos and Breuer 1996):

$Kn < 0.01$	Continuum flow
$0.01 < Kn < 0.1$	Slip flow
$0.1 < Kn < 3$	Transition flow
$Kn > 3$	Free-molecule flow

We are focusing our initial efforts on developing the capability to obtain quantitative velocity profiles in a two-dimensional N_2 nozzle with exit dimensions of order 1 mm (high) x 5 mm (span) and throat dimensions determined by the Mach number of the nozzle. Table I shows free stream static parameters and Reynolds number (based on 1 mm exit dimension) at the nozzle exit at Mach 2 and Mach 4 as a function of stagnation pressure and temperature, assuming an isentropic expansion within the nozzle with specific heat ratio, γ, equal to 1.4. These two Mach numbers have been selected, preliminarily, in order to evaluate viscous effects within the nozzle as a function of density and to provide a convenient means for spanning flow regimes from continuum to transition. As can be seen in Table I, at Mach 2 stagnation pressure in the range 1.0 - 0.01 atm provides a Knudsen number which ranges from 0.00025 (continuum) to 0.025 (slip). At Mach 4 the same stagnation pressure range results in a range of Knudsen number from 0.002 (approaching the low end of the continuum) to 0.20 (transition). The corresponding gas kinetic mean free path ranges from a low of 0.25 microns, in the Mach 2 case, to 200 microns in the Mach 4 case (Vincenti and Kruger, 1982).

Mach	P_0 (Atm)	T_0 (K)	P_s (Torr)	T_s (K)	R_e	N_o (cm^{-3})	λ (microns)	Kn	Regime
2	1.0	298	100	165	1500	6.2×10^{18}	0.25	0.00025	C
2	0.10	298	10	165	150	6.2×10^{17}	2.5	0.0025	C
2	0.010	298	1	165	15	6.2×10^{16}	25	0.025	S
4	1.0	298	5.0	70	300	7.5×10^{17}	2	0.002	C
4	0.05	298	0.25	70	15	3.8×10^{16}	40	0.04	S
4	0.01	298	0.05	70	3	7.5×10^{15}	200	0.20	T

Table I

Free Stream Conditions For N_2 Flow at Mach 2 and Mach 4.

As will be described in the next section, the diagnostic component of the work performed during this contract focused on velocity field measurements, employing what is known as Molecular Tagging Velocimetry (MTV). MTV is a time-of-flight" technique in which a laser is used to "write" a line (or set of lines) into a flow by means of an optical resonance with a suitable target tracer molecule. A particularly simple gas phase MTV technique has recently been presented by Stier and Koochesfahani (1999). This approach utilizes molecules such as biacetyle or acetone, which due to their relatively high vapor pressures at room temperature (~5 torr), can be readily seeded into gas phase flows. Upon absorption of a photon in the 240 - 340 nm range, both biacetyl and acetone exhibit relatively long-lived radiative emission (0.10 - 1.0 msec) in nitrogen flows (The fluorescence is rapidly quenched in the presence of oxygen). Velocity is determined by imaging the fluorescence from the initially excited line a suitable time delay after excitation. The measurement requires only a single modest power pulsed near UV laser (order 1-2 mJ) for the tagging step, and a gatable, intensified CCD camera for the subsequent imaging (or "interrogation" step.

Gas phase MTV had been utilized in a variety of flow environments previous to this work, but the application to micro scales introduced significant challenges, which needed to be addressed. The most significant issue is the inherent trade-off between obtaining sufficient signal level and achieving the desired spatial resolution. Put simply, as the measurement volume is reduced, the total signal detected per resolution element of the CCD detector drops significantly (Signal essentially scales as the volume, or resolution element cubed). Additionally, the inherent low static densities characteristic of large Knudsen number flow further limit the observed signal. It is also important to quantify the effect of cluster formation in the supersonic nozzle on the fluorescence intensity and lifetime. It was anticipated, although by no means certain, that at least in the Mach 1 - 2 case, the onset of condensation could be delayed sufficiently to permit measurements at the nozzle exit plane. As evidenced by the images in the next section, this has been confirmed, at least for the sonic case. At higher Mach number condensation can be eliminated, if required, by heating the plenum gas mixture. At Mach 2 the stagnation temperature would have to be ~ 550K, which should not be particularly difficult. Finally, since physical dimensions are small, minimization of background interference, particularly that due to fluorescence from facility windows, needed to be addressed.

While the accuracy and spatial resolution of flow tagging techniques can be quite high, the technique is inherently constrained to measurements along a line or, at most, a grid of intersecting lines. Over the past several years, major progress has been made at OSU in the development of Planar Doppler Velocimetry (Elliott et al. 1994, Clancy and Samimy, 1997, Clancy et al. 1999, Samimy and Wernet 2000), a spectrally resolved scattering technique which measures instantaneous, three-dimensional vector fields in a plane, by employing a narrow linewidth laser and a molecular vapor filter, which serves as a spectral discriminator. Compared with other particle-based scattering techniques, application of PDV to supersonic flow has the advantage that individual particles need not be tracked, so that high densities of small particles (order 100 angstrom) can be employed. A second inherent advantage is that there is no particular difficulty associated with making measurements in three-dimensional flowfields, since out of plane motion can as easily be measured as in-plan motion.

Again, while PDV has been successfully employed by a variety of researchers over a wide range of physical scales and flow conditions, the application to micro-scales presents its own set of challenges. It is anticipated that, if renewed, the follow on program will initially focus on the problem of achieving sufficient seed density. In the past, most PDV measurements performed at OSU have relied on natural condensation , such as that from ambient or seeded water vapor, acetone, (Elliott et al., 1994, Clancy and Samimy, 1997) or carbon dioxide (Erbland et al., 1997), which often accompanies supersonic expansion. It is recognized, however, that given the small length scales characteristic of micro-scale nozzles, the dynamics of nucleation may limit the range of flow conditions and/or spatial locations where natural condensation will occur. In cases where condensation is not sufficient, we plan to utilize more traditional particle seeding (For example, monodisperse 25 nm particles are available commercially from Duke Scientific Corporation).

Results From the Present Program

Work performed during the present contract period focused on:

i. Design and fabrication of a simple supersonic flow facility, for use, primarily, as an optical diagnostic development test bed.
ii. Demonstration of MTV in a straight nozzle at static pressure as low as order 1 torr.
iii. Design and fabrication of a one mm scale two-dimensional converging – diverging nozzle.
iv. Initial development of in-house Navier-Stokes and Direct Simulation Monte Carlo computational codes.

Each of these tasks will be described in more detail below.

Task 1: Optical Test Bed

The optical test bed is illustrated in Fig. 1, which shows a scale drawing of the complete facility on the left and a blow-up of the test section on the right.

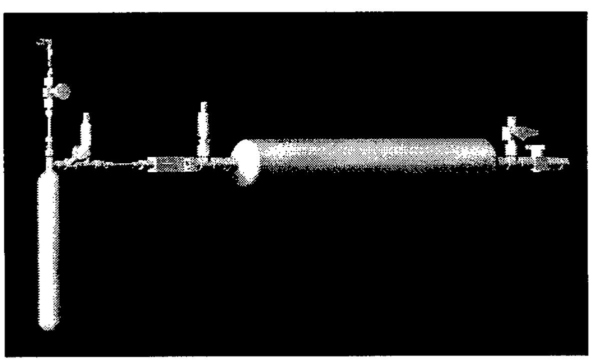


Figure 1a
Drawing of OSU micro nozzle supersonic flow facility.

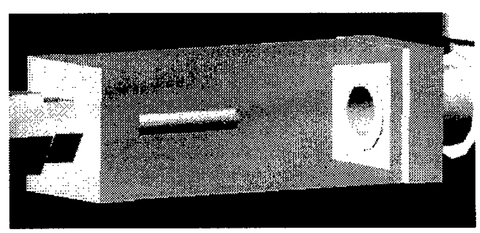


Fig 1b
Blow-up of micro nozzle test section. Dimensions are 1" x 1" x 4" and features four sided optical access.

The facility consists of a vertically oriented volatile vapor seeding cylinder (far left in Fig 1a), 1" x 1" x 4" rectangular test cell, with four sided (supersil low fluorescence quartz) optical access, a five liter cylindrical "dump" tank, an eight SCFM vacuum pump, and three pressure transducers. Test gases are delivered from standard laboratory cylinders. While we have plans to add a facility heater, at the present time the test gases are delivered at ambient room temperature. Nozzles are inserted into the test cell by means of standard fittings. As an initial test case for molecular tagging, a 1 mm ID straight cylindrical tube served as the "nozzle", as indicated in Fig. 1b. While not shown if Fig. 1b, a small pressure tap was drilled into the nozzle wall, close to the exit (~ 1 mm). Additional pressure taps were included in the "plenum" and in the "test section."

Task 2: MTV Demonstration:

At the suggestion of Prof. M. Koochesfahani (Dept. of Mechanical Engineering – Michigan State University), MTV measurements were performed using acetone as the tracer species, since it has a higher vapor pressure than biacetyl and is somewhat easier to work with. Figure 2 shows a pair of MTV images obtained from the 1 mm straight nozzle when operated underexpanded, with nitrogen at the test gas (ie, P_{exit} is greater than the backing pressure of ~10 torr). (Unfortunately, in this case, our nozzle exit pressure transducer had not yet arrived so that exit pressure could not be measured). Approximately 8 mJ/pulse @ 266 nm from a small, pulsed Nd:YAG laser was focused (with a 50 mm lens) to an ~ 20 - 30 micron diameter waist at a location ~ 0.75 mm (3/4D; D is the nozzle exit diameter) downstream from the nozzle exit. Fluorescence from the acetone seeded N_2 flow was captured at an angle of 90^0 with an Intensified CCD camera and a 50 mm focal length, f/1.8 Nikon visible lens. Note that the ICCD camera consists of an 18 mm diameter photo cathode, lens coupled (and reduced) to a 10 mm x 10 mm CCD sensor. By employing suitable extension rings, the Nikon imaging lens is used as an ~ 3X "microscope" which maps the 6 mm x 6 mm "object" plane (ie, the flow field) to the ~18 mm x 18 mm ICCD "image" plane. Internal optics then map the intensifier output to the CCD sensor, resulting in a **spatial resolution of ~12 microns**. The image on the top left shows the initial line writing position and the image on the top right shows the displaced line 450 nsec later. The flow is from right to left, which can be seen more readily in the digitized traces shown in Fig. 3, each of which is a single horizontal cut through the line at a location near the vertical centerline of the nozzle. The observed displacement is 200 microns (or 16.67 pixels), resulting in a centerline velocity of ~440 m/sec. While it is not been verified, we can estimate the statistical uncertainty by assuming that the displacement can be measured to the nearest 0.20 pixel. This corresponds, in this case, to an uncertainty of order 5 m/sec or ~1%. Note that it is hypothesized that the sharp intensity decrease outside the core flow region is due to high pressure quenching of the LIF.

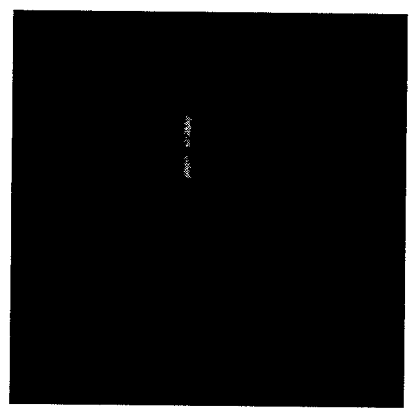


Figure 2 Acetone MTV image pairs from underexpanded 1 mm ID straight jet. Stagnation pressure is ~ 30 torr and flow is from right to left. The left image corresponds to the original "writing" position and the right is the position of the "tagged" fluid 450 nsec later.

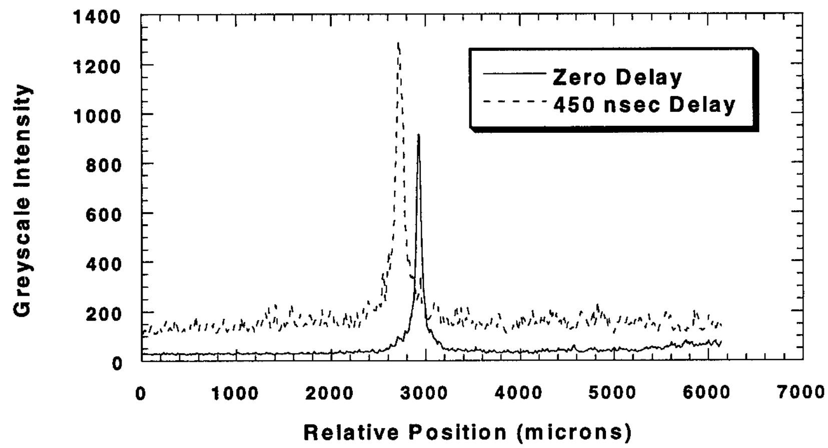


Figure 3: Grey scale intensity from single horizontal cuts through each of the images in Fig. 2. Observed velocity is ~ 440 m/sec. Flow is from right to left (ie, decreasing position).

Figure 4 shows a similar set of acetone MTV images which were obtained at factor of two higher spatial resolution (~ 6 microns/pixel). In this case, the nozzle was operated at near Mach 1 (near pressure matched), with exit pressure (which was measured) and back pressure equal to ~ 4 torr. As can be seen from the centerline horizontal grey scale slices shown in Fig. 5, ~100 microns of displacement is observed in 300 nsec, corresponding to a measured velocity of ~330 m/sec. This compares favorably with the predicted sonic speed of ~320 m/sec. It should also be noted that the effect of mass diffusion on the tagged fluid element is clearly evident in the image sequence of Fig. 4.

The data of Figs. 2 - 5 represent, to our knowledge, the first demonstration of MTV in compressible flow. That this data could be obtained (relatively quickly and easily) at 4 torr pressure and with spatial resolution of order 10 microns (or less) clearly demonstrates the potential of the technique.

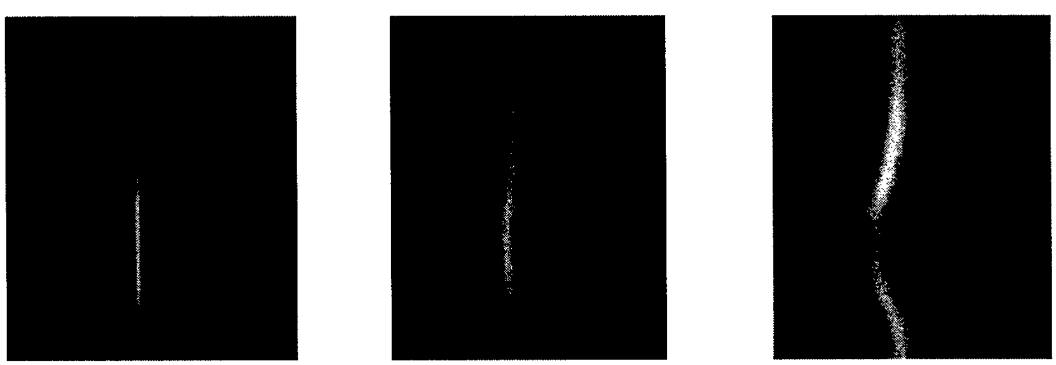


Figure 4: MTV Images obtained in near pressure matched 1 mm jet at higher resolution. Exit Pressure is ~ 4 Torr and Field-of-View ~ 3 mm x 3 mm. Images correspond to initial writing position (left), displacement after 300 nsec (middle) and 800 nsec (right). Flow is from right to left.

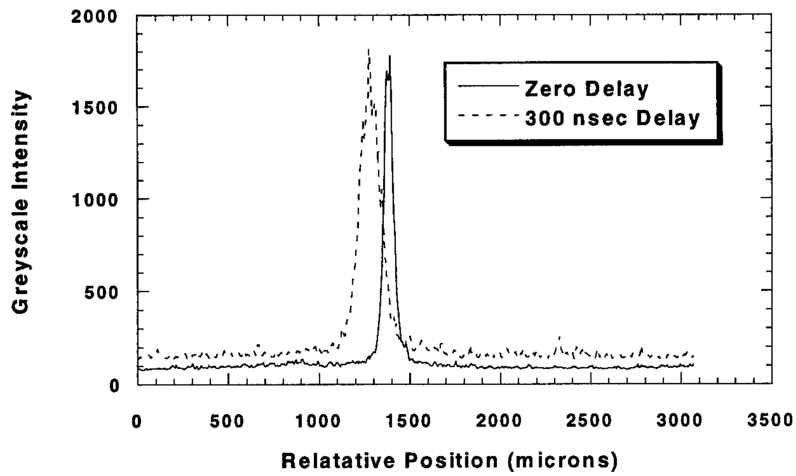


Figure 5: Grey scale intensity from single horizontal cuts through the left and middle images in Fig. 4. Observed velocity is ~ 330 m/sec. Flow is from right to left.

Task 3: Mach 2 Nozzle Design: We have also designed and fabricated a Mach 2 C-D nozzle, a top view of which is given in Fig. 6. The nozzle was fabricated by etching a 2-D contour from top to bottom through an aluminum block, using the Electric Discharge Machining (EDM) technique. Pending follow on support, quartz windows will be bonded to the top and borrom, following an approach described by Bayt and Breuer (1998). The nozzle will then be inserted into the diagnostics development facility, and MTV and PDV measurements performed, initially in the exit plane, and, subsequently, internal to the nozzle.

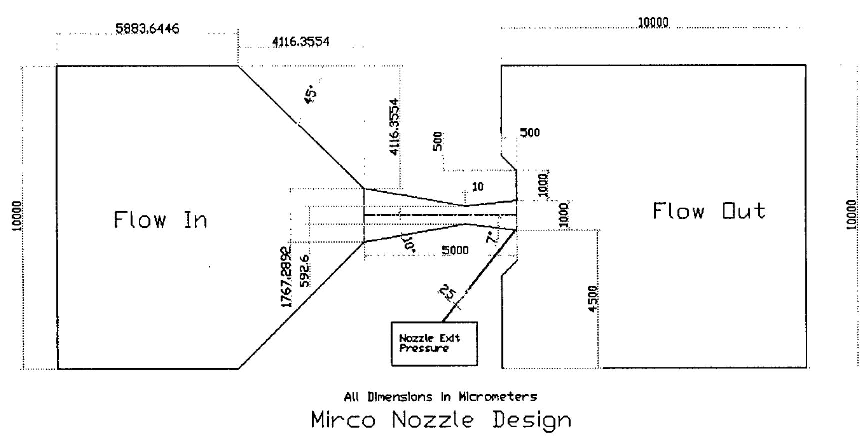


Figure 6: Top view drawing of Mach 2 C-D Nozzle. All dimensions are in microns.

Task 4: Code Development: We have performed some preliminary Navier-Stokes computations, using both a commercial package (Star CD) and a two-dimensional code developed at OSU (Aithal and Subramanium, 2000) with previous AFOSR support. Figure 7 shows a sample prediction of the nozzle exit velocity profile, assuming the geometry of Fig. 6 and stagnation pressure and temperature of 1 bar and 300 K, respectively. The free stream velocity corresponds to a Mach 2 flow, with a boundary layer thickness of order 50 microns.

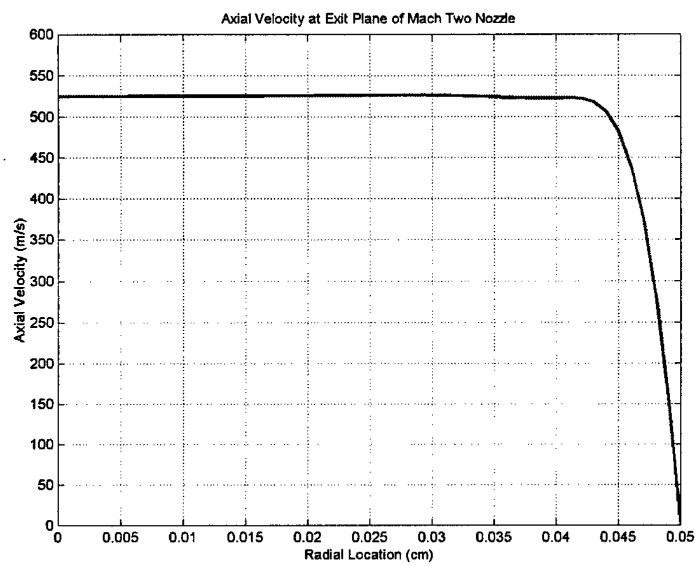
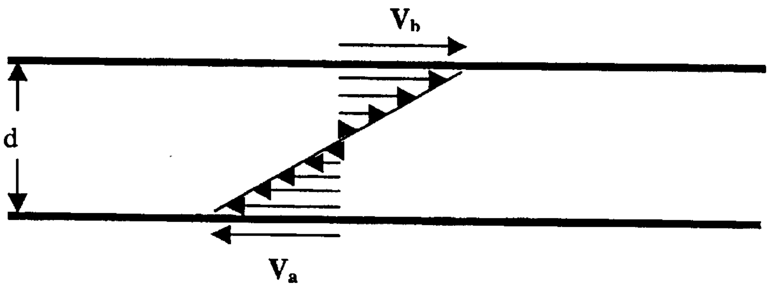


Figure 7 Sample Navier-Stokes prediction of velocity profile at exit of pressure matched Mach 2 nozzle.

We have also begun efforts to develop an in-house DSMC code, using an approach similar to that described by Bird (1994). As a numerical test case, Fig. 8 shows a computed two - dimensional Couette flow (flow with constant velocity wall, as illustrated). The governing equation is:

$$\frac{\partial f}{\partial t} + C_i \bullet \frac{\partial f}{\partial x_i} = \left(\frac{\delta f}{\delta t}\right)\Bigg|_{\substack{molecular\\collisions}} + \left(\frac{\delta f}{\delta t}\right)\Bigg|_{\substack{collisions\\with\ walls}}$$

where f is the velocity distribution function, which evolves in time due to convection (2^{nd} term on left), binary collisions between molecules (first term on right) and molecular collisions with walls (second term on right). It can be seen from Fig. 8, that the code is capturing a finite velocity slip and increased velocity gradient in the near wall region.



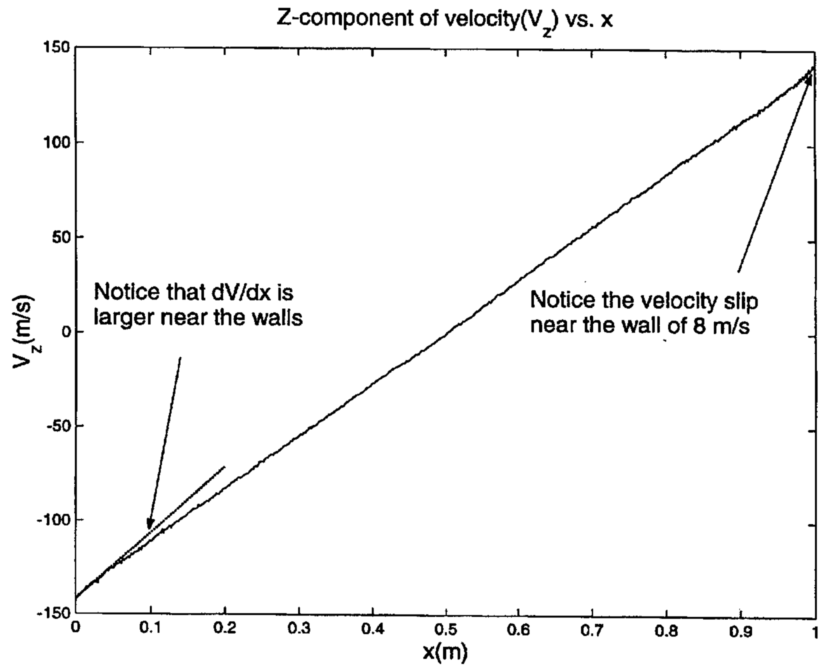


Figure 8: Sample output of OSU DSMC code, illustrating velocity slip in near wall region of Couette flow.

Personnel

The co-PIs are Walter Lempert, Mo Samimy, and Vish Subramaniam, of the Department of Mechanical Engineering at Ohio State University. (W. Lempert has a joint appointment with the Dept. of Chemistry). The majority of the experimental portion of the work was performed jointly by undergraduate students, Mr. Samuel Merriman and Mr. Adam Christian. The DSMC work was performed by a third undergraduate student, Mr. Mathew Buoni. Dr. Mohamed Elsharnoby, a visiting scientist, led the CFD effort. In October, two new Ph'D students began work on the project for whom it is anticipated that follow on work will constitute the bulk of their thesis.

FY00 Publications

An abstract, entitled "Development of Velocimetry Techniques for High Speed Flows In Micro Systems ", has been accepted for presentation to the 39th AIAA Aerospace Sciences Meeting, Reno, NV, January, 2001. A manuscript is in preparation, for submission to the AIAA Journal.

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